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Biomass gasification in a downdraft gasifier with a two-stage air supply: Effect of operating conditions on gas quality

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ABSTRACT

The gasification of the biomass is an attractive technology for the production of electricity, heat, chemicals and liquid fuels. This paper presents an experimental evaluation of the quality of the producer gas in a two-stage, air supply downdraft gasifier, referred to its tar and particle content for different operating conditions. The gas composition and its lower heating value were also determined. Experimental tests were performed varying the operating conditions of the gasifier: the air flow between 18 Nm^3/h and 22 Nm^3/h (the proximate equivalence ratio from 3.03 to 0.279) and the air flow ratio in the two stages (AR) between 0% and 80%, evaluating the effects of these parameters over the quality of the gas. The results show that a fuel gas, with tar and particulate matter content of 54.25 ± 0.66 mg/Nm^3 and 102.4 ± 1.09 mg/Nm^3, respectively, was obtained, for a total air flow rate of 20 ± 0.45 Nm^3/h and an air ratio, between the two stages, of 80%. For these conditions, the lower heating value of the gas was 4.74 ± 0.5 MJ/Nm^3. The two stage air supply in the gasification allowed to reduce the tar content in the producer gas up-to 87% with even a slight increase in the gasifier efficiency. This results can be explained by an increase of the temperatures in the pyrolysis and combustion regions.

1. Introduction

In 2009, renewable energy sources represented 16% of all global consumption of primary energy, and 10% corresponded to biomass [1]. The use of forest biomass and of agricultural or animal residues as a source of energy, is an important part of sustainable development policies in developed and emerging countries, that will contribute to lower their energy dependency on fossil fuels and in such a way reducing greenhouse gases emissions. One of the technically feasible ways to convert the biomass into fuels is the gasification, that consists in the conversion of biomass into a fuel gas through it partial oxidation at high temperature. The composition of this gas depends on several factors such as the type of biomass used in the process, the temperature and the type of gasification agent [2]. This gas also contains impurities such as tars, particles, nitrogen (NH_3, HCN) and sulfur (H_2S, COS) compounds. Tar is undoubtedly the greatest technical barrier

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Nomenclature

AR	ratio between first and second stages air flows (%)
k_p	coverage factor
LHV	lower heating value of the producer gas (MJ/Nm^3)
n	number of repetitions in a test
u_c	combined uncertainty
U_p	expanded uncertainty
$(Va)_{1st}$	air flow through stage 1 (Nm^3/h)
$(Va)_{2st}$	air flow through stage 2 (Nm^3/h)
Greek letters	
$\sigma_{(n-1)}$	standard deviation of the replicates or measurements

because of its physical and chemical characteristics (high viscosity and molecular weight) that make the gas not feasible to be used in direct applications in thermal engines. So, the tar removal is a main technological task; the methods for tar removal can be divided into two groups: primary methods where cleaning occurs within the gasifier and secondary methods where gas cleaning is performed after the gasification process by a secondary treatment [3]. Considering the primary method of tar removal combined with thermal cracking (a high temperature process to break the compounds of the tar), a two-stage gasification system was developed, which is based on the injection of the gasification fluid in and additional location, than the combustion zone, i.e. in the pyrolysis zone, leading to the partial oxidation of the biomass in this region, that give higher fuel gases concentrations and very little tar content.

The Asian Institute of Technology (AIT) designed a two-stage air supply gasifier, that allows to obtain a gas with a tar content approximately 40 times lower than the one produced in a conventional gasifier [4,5]. Jaojaruek et al. [4] studied the eucalyptus biomass gasification in a downdraft gasifier using three different configurations: single stage (SS), two-stage air supply (AA) and two-stage air and air-gas (AG). The tar content in the gas produced in the system was 1270 mg/Nm^3 for SS, 114.4 mg/Nm^3 for AA and 43.2 mg/Nm^3 for AG. Variations in ER optimum values for the different operational regimes were presented. Bhattacharya et al. [5] studied the wood gasification in a downdraft gasifier operated with different primary and secondary air flows ratio and observed that the tar yield is strongly dependent on the secondary air. The Technical University of Denmark designed another type of two-stage gasifier, characterized by having two separated reactors: the first where the pyrolysis takes place and the second where the partial oxidation occurs, allowing to get in extremely low tar concentrations in the produced gas (15 mg/Nm^3) [6]. Raman et al. [7]. in a two-stage gasifier reached tar content values in the gas of 63 mg/Nm^3. Ma et al. [8] presented the results of the tests carried out in another two-stage gasifier, highlighting that an increase in the producer gas calorific value was observed.

This paper reports the results of the experimental work done to extend and complete the results of the researches carried out by Martinez et al. [9], Lesme et al. [10] and Andrade et al. [11] using the same gasifier, that reported the influence on the gas composition, its heating value and the gasifier efficiency of the reactor operation at single and two-stage air supply regimes. It was found that a maximum efficiency values occurred when the gas flow was 20 Nm^3/h and 22 Nm^3/h (ER of 0.4 and 0.39) respectively. Gas quality evaluation through tar and particle content was not carried out in Ref. [9].

As a remarkable difference from previous studies is that in this case there was an interest to confirm that at a two-stage gasification, the main gas quality indexes, such as tar and particle content, are linked to the gasifier operational parameters (Air flow/ER and the air distribution among the two stages AR).

The objective of this study was to determine the effect of different operation regimes of the two-stage air gasifier, on the tar and particle content of the producer gas. Also verifications of the optimum operational point, considering simultaneously the efficiency of the equipment and the gas quality as performance criteria. The downdraft *gasifier is installed in the NEST's laboratory of the Federal University of Itajubá*. An uncertainty analysis for determining the average measurements errors was performed.

2. Materials and methods

2.1. Biomass characterization

The biomass used in the tests of this research work was Eucalyptus wood in the form of dices of nearly cubic shape with the greater size no larger than 6 cm. This size was defined as a result of previous gasifier operational campaigns experience, in order to avoid empty spaces in the biomass bed, leading to solids movement interruption and also to ensure a free gas flow though the biomass bed.

The analytical data of ash, volatile and fixed carbon content, as well as the elemental analysis (carbon, hydrogen, nitrogen, oxygen and sulfur) and the determination of the lower heating value of the biomass were performed in the NEST/UNIFEI laboratories.

During the biomass characteristics determination the following equipments were used:

Table 1 – Experimental data of the Eucalyptus biomass characterization (dry basis).

Parameter	Value
Proximate analysis (wt %)	
Ash	1.34
Volatile matter	83.01
Fixed carbon	15.66
Elemental analysis (wt %)	
Carbon	46.78
Nitrogen	0.324
Hydrogen	5.92
Sulfur	0.09
Oxygen	45.55
Moisture (%)	12.23
LHV (kJ/kg)	18,058.36

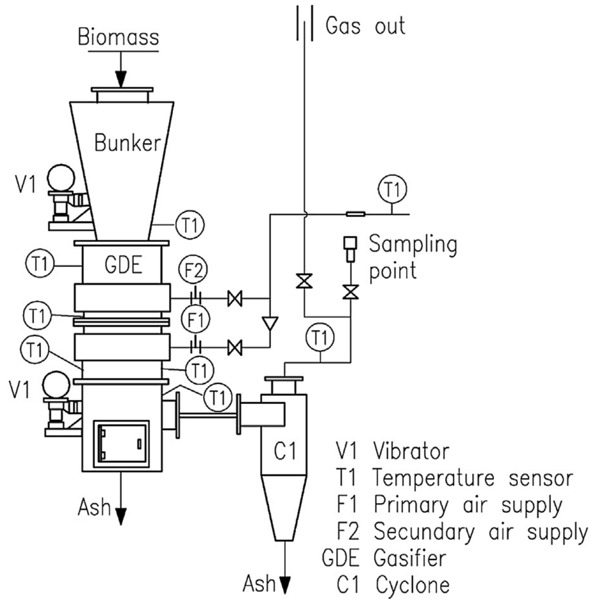

Fig. 1 – Schematic of the gasification system.

- Proximate analysis: Thermobalance. Model TGA 701, manufactured by LECO, United States, (2012).
- Elemental analysis: CHNSO, Model 2400, manufactured by Perkin Elmer, United States, (2012).
- Lower heating value: Calorimetric bomb, Model C2000, manufactured by IKA, Germany, (2006).

Table 1 shows the proximate and elemental composition of the eucalyptus biomass used in the gasification and its lower heating value.

2.2. *The gasification system and instrumentation description*

2.2.1. *The gasification system*

A double stage downdraft gasifier, manufactured by the Brazilian Company "Termoquip Energia Alternativa Ltda", was the equipment used in the tests, with an internal diameter of 0.3 m and a height (from the top of the reactor to the grate) of 1.06 m. The gasifier is built of carbon steel and has an internal refractory coat. Six K-type thermocouples were installed along the reactor to monitor the temperature reading at different heights. Two thermocouples measure the temperature of the inlet air, another one measures the temperature of the exit gas. The air is supplied by a blower (1.86 MPa). The gases leave the reactor through its lower section, after crossing the gasification zone, the grate and passing through a cyclone where the larger solid particles are removed. The primary air is supplied 0.3 m over the grate and the secondary one 0.4 m over the primary. The length of the pyrolysis zone over the combustion one was determined by analyzing the temperature profiles, inside the reactor, when only a single air supply was used. The mean biomass consumption in the test runs was around 12 kg/h. Two vibrators were attached to the gasifier body, one at the hopper section and the other at the grate one, both with the aim to ensure the smooth flow of the biomass inside the reactor. The gas sampling point is located at the cyclone exit tube. The details of the experimental installation and the position of the thermowells for temperatures indicators in the gasifier are shown in Fig. 1.

2.2.2. *The gas analysis*

The gas composition (CO, H_2 and CH_4) was determined using continuous analyzers ROUSEMONT and MADUR, whose main specification characteristics follow:

- ROUSEMONT – CO, H_2 and CH_4, Model BINOS 100 and HYDROS 100, manufactured by Emerson Process Management, Germany, (2003)
- MADUR – CO_2, CO, H_2 and CH_4, Model MaMos 400, manufactured by Madur electronics, Australia, (2011).

The signals from the gas analyzers are transmitted to a computer, through the data acquisition system, for storing and displaying data every 2 s. The total number of data collected was 240. Before the continuous analyzers, a cleaning

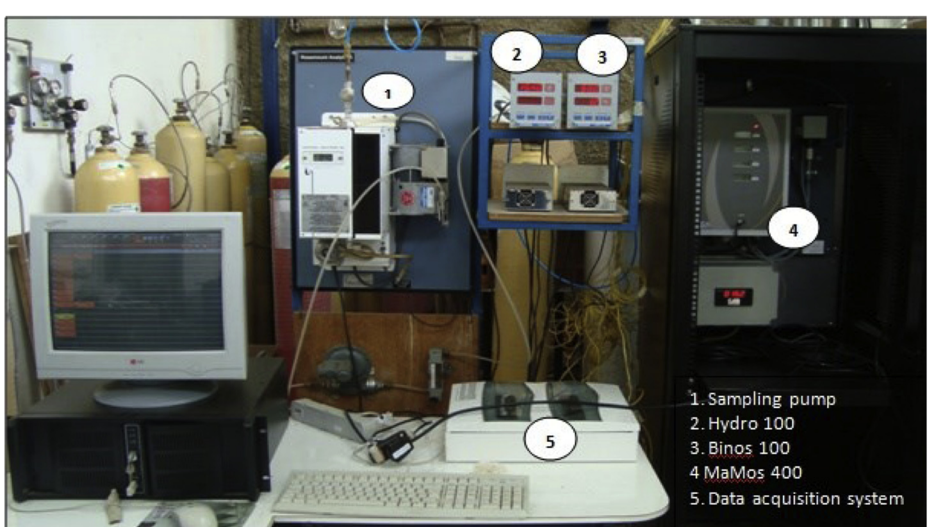

Fig. 2 – System for the gas composition determination.

system is located, that removes the moisture and particles from the gas flow. The analytical system is shown in Fig. 2.

2.2.3. *Tar and particle content determination in the gas*

The sampling of tar and particles was carried out following the European Fifth Framework Programme Report [12], which consists on the isokinetic sampling of the gas, the solids filtration and the tar absorption in a solvent contained in bottles, that are kept at low temperature. A pitot tube, located beside the sampling probe nozzle allows to compare the gas velocities in the gasifier exhaust tube and inside the sampling probe nozzle for the isocinetism compliance verification. The diagram of the sampling line is shown in the Fig. 3.

The module one (1) is the pre-conditioning stage of tar and particles sampling, it consists in an isokinetic tube connected to the gas line, heated with an electrical resistance to prevent the condensation of the tar inside the tube and of a vessel containing the particle filter. The tube and the port filter are heated up to 250 °C. The module two (2) is for the collection of tar; where the gas is conducted to a system of six bottles called "impingers" connected in series. The first impinger is empty, being a moisture collector; the other four impingers are filled with isopropanol, where the water and tar from the gas are condensed. The last impinger is filled with silica to dehumidify the gas. A mixture of common salt, ice and water was used to keep the impingers at a low temperature. The module three (3) comprises a vacuum pump to extract the gas, a flowmeter and a temperature indicator.

The tar and particle sampling is performed when the gasifier reaches the steady state regime. The tar and particles yield is determined by the gravimetric method, and after that a process of soxlhet extraction and evaporation of the solvent is carried out.

2.3. *Gasification process governing variables*

In a two stage gasifier the governing variables are the total air flow, that define the equivalence ratio ER, and the air ratio between the two stages (AR) (equation (1)).

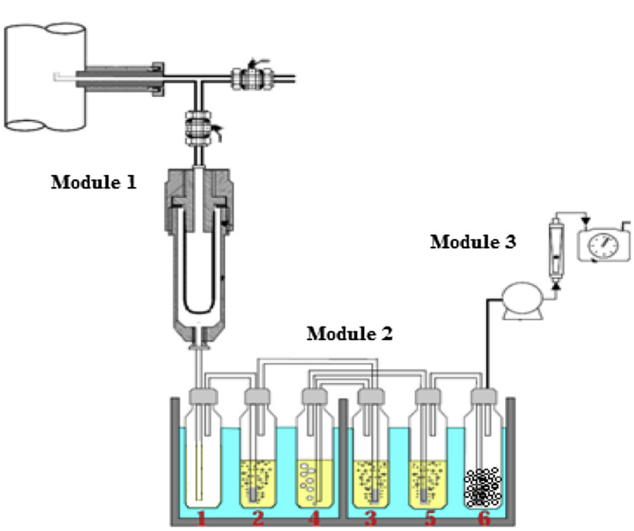

Fig. 3 – The tar and particles sampling system.

Table 2 – Experimental planning.

Run	AR (%)	Airflow (Nm^3/h)		
		$(V_a)_{1st}$	$(V_a)_{2nd}$	Total air
1	0	18	0	18
2		20	0	20
3		22	0	22
4	40	12.86	5.14	18
5		14.29	5.71	20
6		15.72	6.28	22
7	80	10	8	18
8		11.12	8.88	20
9		12.23	9.77	22

$$AR = \frac{(\dot{V}a)_{2st}}{(\dot{V}a)_{1st}} \times 100 \qquad (1)$$

In this paper the equivalence ratio is used always simultaneously with the total air flow values due to the fact that the batch operation of the gasifier does not allow to define a continuous biomass flow entering the reactor. The calculated values of ER have an intrinsic error in its determination, and can be used only as reference. Even when keeping the total air flow constant and changing the AR it was noticed a slight variation in the biomass consumption and in the ER values. Note that average values for the total air flows of 18 Nm^3/h, 20 Nm^3/h and 22 Nm^3/h will correspond approximately to equivalent ratios of 0.303, 0.279 and 0.289 respectively.

2.4. *Experimental planning*

A 3^2 factorial experimental planning was designed (Table 2), with two factors, each one with three levels, without full replication, for a total of nine tests. The non full replication of the tests was a decision taken due to the fact that it was only possible to carry-out one test per day. The calibration of the gas analyzers and of the isokinetic probe, plus the start-up and the attaining and stabilization of the steady-state regime will take about 3 h. If it's consider that isokinetic sampling takes 1 h and the analytical procedures to get the final tar and particle concentration last more than 4 h, it is

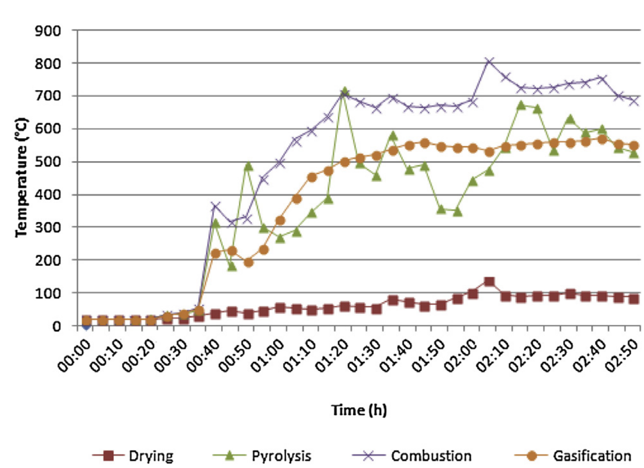

Fig. 4 – Evolution on time of the temperature profile of the gasifier for AR of 0% and total airflow of 20 Nm^3/h.

easy to understand the difficulties of data replication. After all the tests were done, it was carried out an screening of the obtained data, and the doubtful ones, showing non-logical or out of tendency values, related to literature data, were repeated. During all the trials three full tests were repeated.

The factors in the experimental planning are the total air flow and the air ratio (AR); the levels are 18, 20 and 22 Nm^3/h for the total flow of air and 0%, 40% and 80% for the ratio of air.

2.5. *Uncertainty analysis*

The experimental measurements always have associated parameters that influence the certainty of the results. Because of that, the uncertainty of each measured parameter was assessed, applying the standard uncertainty according to the ABN and INMETRO Standards [13]. The main sources of uncertainty in biomass gasification are: the temperature measurements (thermocouples type K), the determination of tar and particles content in the gas, the determination of the gas composition (H_2, CO, CH_4), the calculation of the lower heating value of the gas from its composition and the measurement of air flow (Temperature, Pressure, expansion coefficient of the air and air density). In the case of the air flow measurements uncertainty the ISO 5167-1 [14] and 5167-2 [15] was used.

Generally, the calculation of uncertainty needs the definition of the components that affect it, the determination of standard and combined uncertainty to finally obtain the expanded uncertainty of the process variable, according to the equations 2 and 4.

Standard Uncertainty

$$u_A = \frac{\sigma_{n-1}}{\sqrt{n}} \tag{2}$$

so the combined Uncertainty

$$u_c = \sqrt[2]{\left(\frac{\partial y}{\partial x_1} \times u_{x1}\right)^2 + \left(\frac{\partial y}{\partial x_2} \times u_{x2}\right)^2 + \cdots \left(\frac{\partial y}{\partial x_N} \times u_{xN}\right)^2} \tag{3}$$

The U_{xi} values (i = 1,2, … n) represent the individual uncertainties in the measurement of each variable, directly measured and the partial derivative of y with respect x_i it's called the sensitivity coefficient.

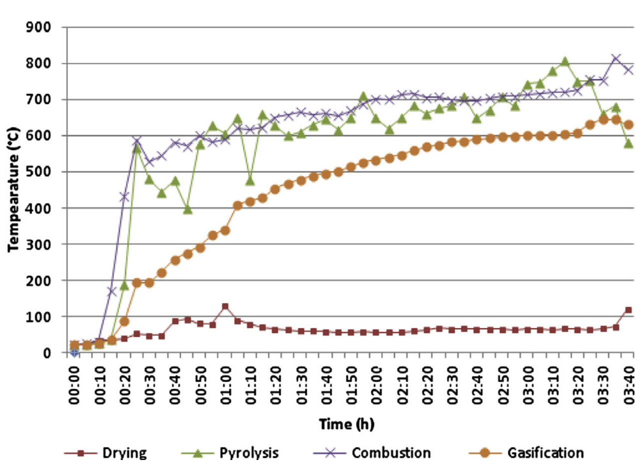

Fig. 5 – Evolution on time of the temperature profile of the gasifier for AR of 80% and total airflow of 20 Nm^3/h.

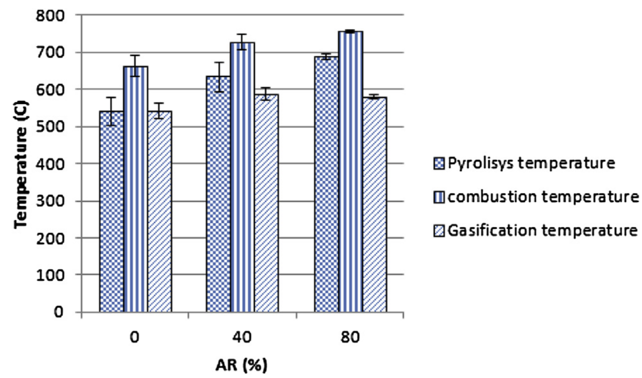

Fig. 6 – Effect of AR on temperature values in the different gasifier zones for an air flow of 20 Nm^3/h (ER = 0.279).

The expanded Uncertainty

$$U_p = u_c(y) \times k_p \tag{4}$$

The coverage factor can vary between two and three, depending on the confidence level.

3. Results and discussion

3.1. *Temperature profile in the gasifier*

Figs. 4 and 5 show the performance of the gasifier based on the record of the temperatures in different zones from the beginning of the start-up process up-to the steady state condition, for a total air flow of 20 Nm^3/h and air ratios AR of 0% (single-stage) and 80% (double stage). The temperatures in the gasifier were measured using thermocouples located inside, but near, the walls of the reactor, with the aim to not interfere with the biomass movement. So the absolute temperature values does not exactly correspond of the temperature of the gas inside the reactor. These measurements are used only to verify the moment when the gasifier reaches it steady state operation or in the form of differential temperature between the gasifier zones to explain and to improve the effect of two stage operation on gas quality.

In Figs. 4–6, it can be observed that the use of a second stage of air supply in the gasifier increases the temperature in the pyrolysis zone, approaching that of the combustion zone. Average values of the different zones temperatures for all the tests are summarized in Fig. 6. The average temperature in the pyrolysis zone was 539 °C and 686 °C for an AR 0% and 80% respectively, while the temperature in the combustion zone reached 750 °C approx. This behavior suggest a reduction in the amount of tar formed during the pyrolysis process to be possible as it should promote the cracking of tar in the combustion zone.

As shown in Fig. 6, in both the combustion and the pyrolysis zones the average temperatures increase when operating in the two stage air supply, compared to the values for the single stage regime. Although the highest temperature increase corresponds to the pyrolysis zone. It was found that when operating within the range of AR = 0 and AR = 80, it corresponds to 147 °C. This figure includes also bars showing

Table 3 – Composition and LHV of the gas.

Parameters	Units	Resulted								
		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
AR	(%)	0	0	0	40	40	40	80	80	80
Air flow	Nm^3/h	18	20	22	18	20	22	18	20	22
Pyrolysis temp.	°C	527.25	539.40	592.64	608.06	633.64	689.39	644.16	686.69	768.92
Gasification temp.	°C	553.97	540.95	586.12	577.16	587.26	696.74	552.32	579.83	668.77
Combustion temp.	°C	715.81	663.71	706.39	743.99	727.03	793.56	772.71	757.95	777.96
CO	% vol.	15.15	18.59	16.67	18.3	20.73	20.9	17.6	19.2	19.08
CH_4	% vol.	1.71	1.72	1.87	2.05	1.85	1.82	1.38	1.3	1.35
CO_2	% vol	15.36	13.32	13.53	15.39	13.52	12.08	15.13	14.22	13.47
H_2	% vol.	14.62	17.71	15.41	14.88	16.61	16.91	15.38	17.14	16.15
LHV	MJ/Nm^3	4.11	4.87	4.9	4.65	5.08	5.12	4.38	4.74	4.64
Tar	mg/Nm^3	1269.70	418.95	144.71	76.09	104.99	78.57	171.49	54.09	90.24
Particles	mg/Nm^3	216.45	146.04	176.04	142.39	107.16	164.99	97.19	102.4	264.2

the uncertainty of the temperature measurements, that are different for different AR values, due to an stabilization of temperatures with the increasing of the AR.

From Figs. 4 and 5 it can be concluded also that the operation in two-stage regime allows a faster start-up of the gasifier.

When the gasifier is operated with the air supplied only to one stage, the temperatures of the pyrolysis and gasification zones depend on the heat released by the combustion zone, where the air is supplied. With the addition of a second stage with an air supply just above the normal point, there is an increase of the temperature in the pyrolysis zone, that now is not only benefited by the heat released by the combustion and becoming a new "combustion zone" as shown in Fig. 6. In the other hand, increasing the AR value and maintaining a constant total air flow, the temperatures in different zones of the gasifier (pyrolysis, gasification and combustion) show an increment proportional to the variation of the AR, improving the conditions for tar cracking. However, as the total air flow remains the same, while changing the AR, no reductions in the gasifier efficiency were observed up to an AR value of 40%. Martinez at al [9]. reported a slight increase in efficiency and Ma et al. [8] reported an increase in the heating value of the producer gas both these facts related to the tar conversion by thermal cracking into gases.

3.2. *Gas composition and lower heating value*

The gas composition (CO, CH_4, H_2) was evaluated at three (3) different values of AR, (0%, 40% and 80%). Table 3 shows the average concentrations of CO, CH_4 and H_2 as well as the LHV of the gas.

Figs. 7 and 8 show the effects of the total flow of air and AR on the composition and the LHV of the gas.

According to Fig. 7, the air flow between 20 Nm^3/h and 22 Nm^3/h (ER = 0.279 – 0.289) corresponds to the highest level of CO and the lower methane yield. The highest content of H_2 (17.14%) is obtained at 20 Nm^3/h, when the lower heating value of the gas reach it higher value (LHV = 4.74 MJ/Nm^3). This higher amount of H_2 in the "producer gases" could be a consequence of the tar cracking that increase the H_2 production. It is expected that greater air flows, above 24 Nm^3/h, will favor the combustion reactions and therefore, a reduction of the CO and H_2 content in the gas, as it was observed by Martinez [9]; but not evaluated in our tests. Bhattacharya et al. [7], gasifying Yang wood in a two-stage gasifier, found a similar behavior of the dependence of the gas composition on AR values.

In Fig. 8, it possible to appreciate that the concentration of CH_4 decreases as the AR increases from 40% up to 80%, due to the partial oxidation and reforming reactions; also the CO concentration decreases, due to the completion of combustion reactions, leading to a decrease of the LHV of the gases. Jaojaruek et al. [4] in a downdraft gasifier with two-stage air supply also using eucalyptus biomass as fuel, obtained as a result an increase in CO concentration and a decrease in CH_4 concentration compared with single-stage air supply downdraft gasifier. In addition, LHV for the AR = 80% was almost the same with the one obtained by Jarungthammachote et al. [16] for an AR of 80% with a value of 4.65 MJ/Nm^3 and the composition of CO (20.15 vol%), H_2 (11.96 vol%), CH_4 (1.05 vol %), CO_2 (14.62 vol%).

3.3. *Tar and particle content of the producer gas*

Last two lines in Table 3 shows the tar and particles content in the gas and the effects of the operational parameters of the gasifier on both values. The results about the influence of AR on tar and particles content in the producer gas are shown in Figs. 9–11.

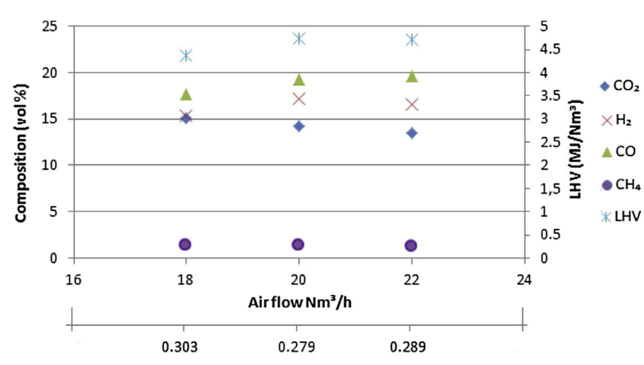

Fig. 7 – Variations of CO, CH_4 and H_2 concentrations and LHV as a function of the total air flow for AR = 80%.

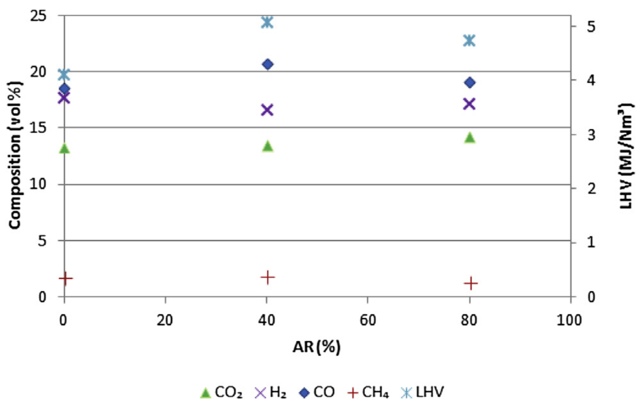

Fig. 8 – Variation of CO, CH_4 and H_2 concentration and LHV as a function of AR for a total air flow 20 Nm^3/h.

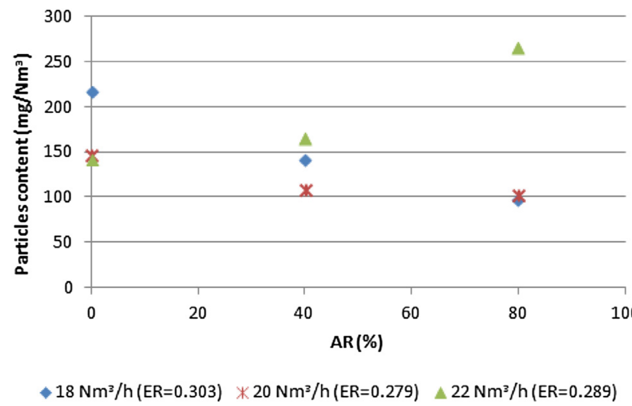

Fig. 10 – Effects of AR and total air flow on the particles content.

In Fig. 9, it can be observed that the highest tar content (1269.64 mg/Nm^3) was obtained for a total air flow of 18 Nm^3/h, which may be related to the low temperature reached at the pyrolysis zone. According to Fagbemi et al. [17], the amount of tar produced reaches a maximum at temperatures of 500 °C in the pyrolysis zone. The results obtained agree with those found by Jaojaruek et al. [4] who have used a two-stage gasifier as a conventional single stage. They found that the tar production was 1270 mg/Nm^3 at 773 °C and 580 °C (combustion and pyrolysis temperature respectively). According to Fig. 9, the tar yield decreases with the increase of the total air flow and AR. It means that the biggest amount of air supplied favors the increase of the temperature inside the reactor and the tar destruction by thermal cracking. In our tests the lowest tar content in the gas was obtained when the gasifier operated with a total air flow of 20 Nm^3/h and the air ratio between the two stages (AR) was 80%.

In Fig. 10 is shown that the variation of AR seems to affect the particle content of the gas in a similar way as the tar content, for an air flow of 18 and 20 Nm^3/h, but for a total air flow of 22 Nm^3/h the particle content increases as the AR increase. This can be explained because of the higher air flows that intensifies the dragging of ash.

Fig. 11 shows the dependence of the tar and particulate content on the temperature in the combustion zone of the gasifier, at an air flow of 20 Nm^3/h. The increase of the temperature in the combustion zone favors the tar thermal cracking, leading to increased production of fuel gases. This temperature increase is achieved by increasing the air flow through the second stage, that favors the increase in the temperature in the pyrolysis zone, providing additional heat to the combustion zone, which agrees well with the results published by Jaojaruek et al. [4] where AR was 100, the tar content 114.4 mg/Nm^3 and the combustion zone temperature 954 °C.

3.4. *Results of the uncertainty analysis of the measured variables*

An uncertainty analysis was carried out for the condition of total air flow of 20 Nm^3/h and an AR of 80% (Run 8). The parameters considered were the temperature, the tar and particles content, the gas composition, the LHV and the air flow, whose uncertainties are shown in Table 4. It can be conclude that the uncertainty values for all parameters show that obtained data have a high level of confidence.

4. Conclusions

The results presented in this paper allow concluding that the two stage air supply in gasification is an effective way to

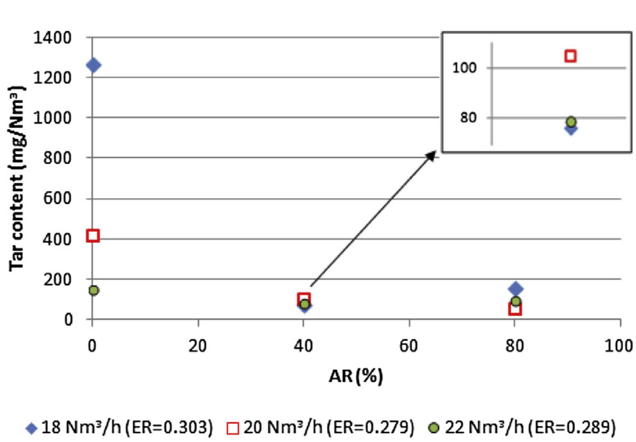

Fig. 9 – Effects of AR and total air flow on the tar content.

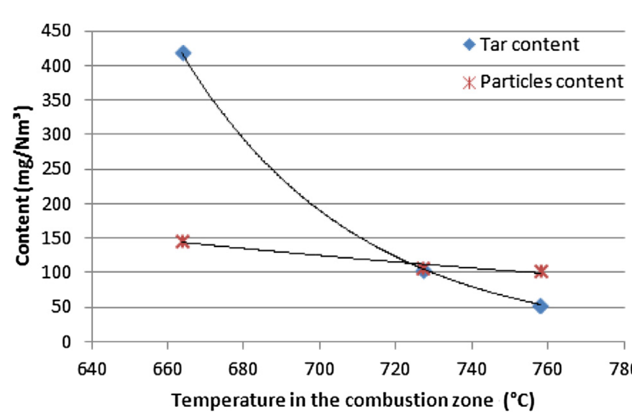

Fig. 11 – Effects of the temperature in the combustion zone on the tar and particle content in the producer gas.

Table 4 – Uncertainty values of the evaluated parameters.

Parameter	Units	Values	Uncertainty
Air flow 1	Nm^3/h	9.43	0.3
Air flow 2	Nm^3/h	14.76	0.46
Total air flow	Nm^3/h	20	0.45
Drying temperature	°C	63.01	1.94
Pyrolysis temperature	°C	686.69	7.87
Gasification temperature	°C	579.83	5.65
Combustion temperature	°C	757.95	4.61
Air flow 1 temperature	°C	35.49	1.16
Air flow 2 temperature	°C	35.49	1.31
H_2	%v	17.14	0.126
CO	%v	19.2	0.357
CO_2	%v	14.22	0.191
CH_4	%v	1.3	0.071
Tar content	Mg/Nm^3	54.25	0.66
Particles content	Mg/Nm^3	102.4	1.09

improve the quality of the producer gas in a downdraft gasifier. When the equivalence ratio (ER) and the air flow ratio between the stages are carefully selected, a slight increase in the gasifier efficiency can be observed.

The two stage air supply effect on the tar and particles content in the producer gas is a consequence of the temperature increase in the pyrolysis and combustion zones. The temperature increase in the pyrolysis zone is much greater and finally leads to the observed increase in the temperature in the combustion zone.

The equivalence ratio, being the main governing parameter in gasification, should be used carefully in downdraft gasifiers, with batch biomass feeding; when the two stage regime is used. It was found that the best solution is to use ER simultaneously with data about the total air flow and the AR. As mentioned before, the lack of a continuous biomass flow just represent an intrinsic error in ER determination. If to add the fact that regimes with different AR values they have different biomass consumption rates, we can conclude about the proximate character of using ER as the only governing variable in this type of gasifiers.

For a total air flow of 20 Nm^3/h and an air ratio between the two stages (AR) of 80%, the gasifier can produce a fuel gas with low tar and particles content from 54.25 to 102 and 4 mg/Nm^3 respectively compared to a tar and particles content of 418.95 and 146.03 mg/Nm^3 obtained for a total air flow of 20 Nm^3/h and an AR of 0%. This result confirms that the use of a second stage air supply enables a reduction of 87% in tar yield and of 29.9% in the particle content of the gas. The producer gas for this operational condition had a composition of 19,2vol% of CO, 1.3vol% of CH_4, 17.14 vol% of H_2, 14.22 vol% CO_2 and with an average LHV of 4.74 MJ/Nm^3.

As the measurements are always influenced by many factors in the studied range, it was advisable and done an uncertainty analysis that gives greater confidence to the obtained results: for a total air flow rate of 20 ± 0.45 Nm^3/h and an AR of 80% a fuel gas with a CO content of $19.2 \pm 0.36\%$ v, CO_2 of $14.22 \pm 0.19\%$v H_2 of 17, $14 \pm 0.13\%$v, CH_4 of $1.3 \pm 0.07\%$ v, tar of 54.25 ± 0.66 mg/Nm^3, particles of 102.4 ± 1.09 mg/Nm^3 and LHV of 4.74 ± 0.5 MJ/Nm^3, was obtained.

The results presented in this paper make possible to fix the parameters to ensure an optimal operation of a downdraft gasifier with two stage air supply, ensuring a high efficiency in the operation and a remarkable quality in the obtained gas. Also, the results are in close agreement with those reported by other scientific institutions and research groups.

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